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JOURNAL OF THE INSTITUTE OF PETROLEUM

FOUNDED 1913 INCORPORATED 1914

Vol. 28 JULY 1942 No. 223

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Published by the Institute of Petroleum.
Address : c/o The Imperial College of Science and Technology, South Kensington, London, S.W.7.
Printed in Great Britain by Richard Clay and Company, Ltd., Bungay, Suffolk.

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Vol. 28. No. 223. July 1942.

SUBSTITUTE FUELS AS A WAR ECONOMY.

Gustav Egloff, F.Inst.Pet., and P. M. Van Arsdell.* †

With the advent of total war throughout the world, the problem of securing sufficient motor fuel of high quality has become vitally important. When the United States entered the war the oil supplies of the Axis group presented a severe contrast to that of the United Nations, who control more than 90 per cent. of the world's petroleum resources.

The world's oil consumers present a different aspect, since the European continent was the second largest user of petroleum and its products before the war began. With the exception of Rumania, Poland, and Hungary, none of the nations under Axis domination has a petroleum industry sufficient to supply its needs, nor have they motor fuel of as high quality as that of the United Nations. The European volume of the world's 2,250,736,000 barrels petroleum production in 1941 was less than 3 per cent., consequently the major portion of their petroleum was previously imported.

The crude-oil production of the world during 1941 is shown in Table I.

When the Axis Powers established domination of the European continent, all oil production, storage, and refinery capacity were confiscated for the German military machine. During 1940–41 practically all the oil-burning motors remaining in civilian use in Europe were converted to the gas-, coal-, and wood-burning type. Progress in building additional plants for the manufacture of synthetic motor fuels also continued. The estimated quantity of petroleum and substitute fuels produced throughout Axis Europe amounted to a maximum of 11,268,000 barrels monthly, and consisted of gasoline from petroleum, hydrogenated coal and water-gas, compressed fuel gases, producer gas from wood, lignite, coal and coke, and alcohol, benzol, and shale oil.

Until Axis control is established in some large oil-producing country, the need for greater quantities of substitute fuels will be present.

The invasion of Russia has cost Germany about 21,250,000 barrels of oil and substitutes per month, of which at least 4,250,000 barrels must be used in maintaining communications and industry behind the battle-lines. It will be noted that Germany is using oil and its substitutes at approximately *double the rate* of their production capacity, which is based on the maximum estimated output of the European continent.

It is estimated that the year's military operations on all European fronts by the Axis Powers called for over 255,000,000 barrels of fuel, of which Germany, Rumania, Poland, Albania, and other occupied countries produced only 53,501,000 [1] barrels of petroleum, and substitute fuels of all kinds equivalent to 81,720,630 barrels of fuel, or a total of 135,221,630 barrels of fuel. From a fuel-production standpoint Axis Europe is short at about the rate of 120 million barrels of oil per year, based on the Russian campaign.

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* Universal Oil Products Company Research Laboratories, Chicago.

† Paper received 20th June, 1942. Presented to Division of Petroleum Chemistry, American Chemical Society at Memphis, April 1942.

TABLE I.

World Crude-Oil Production, 1941.

	1000 Barrels.	Per cent.
North America		
United States	1,405,830	62·46
Mexico	41,200	1·83
Canada	10,003	0·44
	1,457,033	64·73
Central and South America		
Venezuela	222,902	9·90
Colombia	24,442	1·09
Argentina	21,641	0·96
Trinidad	21,211	0·94
Peru	12,846	0·57
Ecuador	1,561	0·07
Bolivia	121	0·01
	304,724	13·54
Europe		
Russia	242,150	10·76
Rumania	40,563	1·80
Germany—		
Old Reich	4,438	0·19
Ostmark	692	0·03
Slovakia and Moravia	109	0·01
Poland	3,319	0·15
Hungary	2,474	0·11
Italian Empire—		
Albania	1,381	0·06
Italy	46	—
France	479	0·02
	295,651	13·13
Asia		
Iran	78,035	3·47
Iraq	12,650	0·56
Burma	7,762	0·34
Bahrein	6,846	0·30
Saudi Arabia	5,871	0·26
British India	2,270	0·11
	113,434	5·04
Oceania		
Netherlands East Indies—		
Sumatra	40,827	1·81
Borneo	13,848	0·62
Java	6,735	0·30
Molucca	721	0·03
British Borneo—		
Brunei	5,552	0·25
Sarawak	1,312	0·06
Japan	2,659	0·12
	71,654	3·19
Africa		
Egypt	7,659	0·34
Other Countries	581	0·03
World total	2,250,736	100·00

From time to time the question arises as to the Axis defeat because of oil shortage. The European continent is low in oil production, and to maintain a campaign based on the strategy of World War No. 1 would have depleted their oil resources. However, with modern " blitz " warfare the Western European campaign lasted but forty-five days from invasion to capitulation. In this forty-five-day war about 12½ million barrels of oil and oil products were used, and the captured stores in the defeated countries were estimated at about 20 million barrels.[2] The remaining European campaigns lasted less than a year—about 284 days of actual fighting up to the time of the Russian invasion on 22nd June, 1941. The actual expenditure of oil up to that date was less than had been expected, based on previous calculations of strategy. In contrast to the Western European campaign, the Russian campaign has cost about 12 million barrels of oil in a similar forty-five-day period, with no oil stores or production gained.

It has been reported that oil stocks in Germany were 59½ million barrels.[3] However, it is not clear as to what the German losses in actual capacity have been from aerial bombardment over Europe by the R.A.F. and the Russian Air Force. From the increasing frequency of bombing raids, the damage to Axis oil production should be relatively large.

A further indication of the prevailing European motor-fuel situation is reflected in a news item appearing in the *New York Times* on 28th April, 1942, describing a system of gasoline barter for Italian prisoners set up by the Yugoslav General Mikhailovitch. According to the dispatch, the system is as follows :

> One Italian soldier or non-commissioned officer for one can of gasoline.
> One Italian officer up to the rank of colonel for four cans of gasoline.
> One Italian colonel for fifty cans of gasoline.

These equivalents were considered unreasonable by the Italian Government, but were finally accepted, thus allowing the General to fuel the tanks captured at the same time as the soliders.

At the beginning of the war, September 1939, Europe had immense stores of crude oil and refined products, and in addition a relatively large synthetic-fuel production.

The extent to which substitute fuels have been necessary is shown by the fact that acetylene, garbage, artichokes, ammonia, and hydrogen are considered suitable for motor fuels, and by the great increase in the number of gas-generator (gasogene) and compressed-gas vehicles during the past two years. It is naturally difficult during war-time censorship and propaganda activities to obtain reliable figures on Axis production and consumption of fuels and fuel substitutes. Data are presented in Tables II and III for maximum and minimum amounts reported by different estimators of fuel substitutes. Both sets of figures are probably tinged with propaganda. The truth most likely lies somewhere between the two sets of data.

Tables II and III show the maximum and minimum fuel-production statistics. Some figures are available only as late as 1939, while others are given for as late as December 1941. In both tables the data presented are estimates.

TABLE II.

Maximum Estimates Axis Oil and Substitutes Production.

	Crude Oil Production.[1]	Hydrogenation, Bergius and Fischer–Tropsch.	Compressed Gases.	Shale Oils.	Benzol.	Alcohol.	Wood and Coal-gas Generators.	Refining Capacity.	Totals Crude Oil and Substitutes.
Germany	5,239,000	42,500,000 [15] [16]	1,785,700 [6]	6,375,000 [16] (pit coal tar motor fuel) + 1,500,000 [6] (gas oil)	5,355,000 [16]	4,000,000 [16]	6,000,000 [5]	24,757,000 [2] (incl. Austria and Czechoslovakia)	72,754,700
France	479,000	3,498,000[4]	238,000 [7]	85,000 [11]	600,000 [6] (1939)	1,600,000 [6] (1939)	1,190,000 [6]	54,558,000 [2]	7,690,000
Hungary	2,474,000	—	—	—	—	80,000 [6] (1939)	—	4,201,000 [2]	2,554,000
Poland	3,319,000	—	—	—	—	100,000 [6] (1939)	—	8,298,000 [2]	3,419,000
Rumania	40,563,000	—	—	—	—	—	—	80,712,000 [2]	40,563,000
Baltic States	—	—	—	1,500,000 [9] (1940)	—	—	—	—	1,500,000
Norway	—	—	—	—	—	—	183,000 [10]	—	183,000
Denmark	—	—	8,500 [11]	—	—	—	277,530 [11]	—	286,030
Holland	—	—	—	—	—	—	42,000 [10]	—	42,000
Finland	—	—	—	—	—	—	238,000 [12]	—	238,000
Belgium	—	—	—	—	300,000 [6] (1939)	—	143,400 [13]	—	443,400
Italy	1,427,000	3,025,500 [14] (1940)	255,000 [8]	—	—	340,000 [3] (1939)	255,000 [3]	20,628,000 [3]	5,302,500
Lithuania	—	—	—	—	—	50,000 [6]	—	—	50,000
Total European	53,501,000	49,023,500	2,287,200	9,460,000	6,255,000	6,170,000	8,328,930	193,154,000	135,025,630

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[1] Anon., *Petrol. Times*, 1942, **46**, 125.
[2] "Petroleum Facts and Figures," 7th Ed., 1941, p. 26.
[3] J. A. Kronstein, *Petrol.*, June 1941, **32**.
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[7] *Chicago Daily News*, 19th March, 1940.
[8] O. Tokayer, *Petrol. Press Service*, Aug. 1941, **8**, 8, 98 (Sec. (6)).
[9] Anon., *Fortune Mag.*, Sept. 1941, **24**, 3, 73.
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[11] Anon., *Foreign Commerce Wkly*, 25th April, 1942, p. 18.
[12] O. Tokayer, *Petrol. Press Service*, March 1941, **8**, 3, 33.
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[14] W. H. Cadman, "Petroleum Technology in 1940," p 140, Inst. Petroleum, London, 1941.
[15] O. Tokayer, *Petrol. Press Service*, 1942, **9**, 4, 42.
[16] L. Lewis, *Petrol. Times*, 1941, **45**, 743.
[17] *Ibid.*, 1942, **46**, 151.

[8] Anon., *Fortune Mag.*, Sept. 1941, **24**, 3, 73.

[17] L. Lewis, *Petrol. Times*, 1941, **45**, 743.
[18] *Ibid.*, 1942, **46**, 151.

TABLE III.

Minimum Estimates Axis Oil and Substitutes Production.

	Crude Oil.	Hydrogenation, Berglus and Fischer–Tropsch.	Compressed Gas.	Shale Oils.	Benzol.	Alcohol.	Wood and Coal-gas Generators.	Totals Crude and Substitutes.
Germany	5,239,000 [1]	19,125,000 [2]	1,429,000 [4]	6,375,000 [6] (pit coal tar) + 1,500,000 [6] (gas oil)	5,355,000 [6]	4,000,000 [6]	1,190,000 [9]	44,213,000
France	479,000 [1]	297,500 [6]	137,700 [6]	85,000 [11]	—	—	—	999,200
Hungary	2,474,000 [1]	—	—	—	—	—	—	2,474,000
	—	—	—	—	—	1,071,000 [6] All occupied countries	—	1,071,000
Poland	3,319,000 [1]	—	—	—	—	—	—	3,319,000
Rumania	40,563,000 [1]	—	—	—	—	—	—	40,563,000
Baltic States	—	—	—	1,300,000 [5] (1939)	—	—	—	1,300,000
Norway	—	—	—	—	—	—	183,000 [7]	183,000
Denmark	—	—	8,500 [10]	—	—	—	277,530 [12]	286,030
Holland	—	—	—	—	—	—	143,000 [11]	143,000
Finland	—	—	—	—	—	—	42,000 [4]	42,000
Belgium	—	—	—	—	300,000 [6]	—	143,400 [6]	443,400
Italy	1,427,000 [1]	631,000 [6]	476,000 [6]	—	—	350,000 [6]	23,800 [6]	2,907,800
Lithuania	—	—	—	—	—	50,000 [6]	—	50,000
Total European	53,501,000	20,053,500	2,051,200	9,260,000	5,655,000	5,471,000	2,002,730	97,994,430

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[1] Anon., *Petrol. Times*, 1942, **46**, 125.
[2] W. H. Cadman, "Petroleum Technology in 1940," p. 140, Inst. Petroleum, London, 1940.
[3] V. R. Garfias and R. V. Whetsel, *Trans. A.I.M.E. Petrol. Div.*, 1941, **142**, 254.
[4] O. Tokayer, *Petrol. Press Service*, March 1941, **8**, 3, 33.
[5] M. Friedwald, *Petrol.*, 1941, **4**, 98.
[6] L. Lewis, *Petrol. Times*, 1941, **45**, 743.
[7] O. Tokayer, *Petrol. Press Service*, 1941, **8**, 11, 134 and 136.
[8] Anon., *Petrol. Times*, 1942, **46**, 151.
[9] Anon., *ibid.*, 1st Nov., 1941, **45**, 628.
[10] Denmark Automobile Census, 18th Sept., 1941.
[11] O. Tokayer, *Petrol. Press Service*, 1941, **8**, 5, 58.
[12] E. A. Bell, *Petrol. Times*, 1941, **45**, 756.
[13] Anon., *Foreign Commerce Wkly*, 25th April, 1942, p. 18.

Composition Motor-Fuel Efficiencies.

On the technical side of the situation the efficiency of the fuels produced as substitutes for the more desirable petroleum products has enforced some limitations on their general adaptability. While it is perfectly feasible to use the various substitutes, there are a number of drawbacks. In compressed gas the weight of the tanks constitutes a decided drain on efficiency. In alcohol fuels separation occurs if water is present, and in the producer-gas vehicle the fuel and the added weight due to the retorts, coolers, etc., are a detriment to efficiency; in addition, an entire new driving and mechanical technique must be learned. Taking into account these major items, the heating quality of the gas is also a considerable item in their use. Table IV shows the heat content of the various fuel substitutes used in the countries without oil.[4] The equivalents are based on one barrel of gasoline as a standard.

TABLE IV.

Heat Content of Gasoline Substitutes.

	Equiv. Bbl. Gasoline 60° A.P.I.
One barrel	
Benzol	1·07
Natural gasoline	0·941—assuming 75° A.P.I. nat. gasoline.
Butane	0·823
Propane	0·730
Ethyl alcohol	0·671
Methyl alcohol	0·507
One thousand cubic feet	
Natural gas	0·219—assuming 1150 B.T.U./cu. ft.
Methane	0·196— „ 1009 „
Manufactured gas (city gas)	0·103— „ 537 „
Producer gas	0·019— „ 100 „

Coal Hydrogenation.

Hydrogenation of coal by the Bergius, and carbon monoxide by the Fischer–Tropsch processes has formed the major source of substitute fuels in Germany. At the present time, in spite of the relatively large installations necessary for fuel production, the Bergius process has the largest production of synthetic oils.

During the years preceding the present war considerable research was done on various hydrogenation processes, and a number of processes for production of oil from coal came into being. The data in Tables V and VI show the development [5] of 1939 through 1940 of Bergius and Fischer–Tropsch processes for the production of oil from coal, their location, capacities, and the year production started. The data are incomplete as to the actual number of plants operating.

The total 1940 figures presented for the hydrogenation processes show that approximately two-thirds of the synthetic oil is manufactured by the Bergius method. Table VI shows the same data for the Fischer–Tropsch process.

TABLE V.

*Hydrogenation (Bergius) Plants in Germany.**

Plant.	Date Placed in Operation.	Place.	Process.	Production (brls.).		
				1938.	1939.	1940.
Leuna, I.G.F.A. . .	1927 or 1933 (?)	Merseburg	Hydrogenation of lignite	3,410,000	3,612,500	4,250,000
Oppau, I.G.F.A. . .	1934	Ludwigshafen	" " "	1,275,000	1,275,000	1,275,000
Wesseling (Cologne Co.) .	1939	Cologne	" " "	—	425,000	1,700,000
Mines of Geiseltal . .	1938 (end)	near Merseburg	Carbonization and synthesis of lignite	—	637,500	637,000
Mines of Geiseltal . .	1940 (end)		Hydrogenation of mineral oils	—	—	637,500
Politz	1940–41	Stettin	Hydrogenation	—	—	2,975,000
Brux	1940–41	Sudetenland		—	—	3,400,000
Bleichhammer . . .	1941	Upper Silesia	Hydrogenation of Polish coals	—	—	—
Magdeburg (Brabag) .	1934	Saxe	I.G. Hydrogenation	3,782,500 with Schwarzheide	5,100,000	5,100,000
Bohlen (Brabag) . .	1937	Saxe	I.G. Hydrogenation			
Zeitz (Brabag) . .	1938 (finished)	Saxe	I.G. Hydrogenation			
Gelsenkirchen . . .	1939	Ruhr	I.G. Hydrogenation	—	637,500	2,550,000
Bottrop	1938	Ruhr	I.G. Hydrogenation	—	—	—
Total . . .				8,467,500	12,112,000	24,225,000

* Anon., *La Revue Petrolifère*, 1924, p. 237.

TABLE VI.

*Fischer–Tropsch Plants in Germany.**

Plant.	Date Placed in Operation.	Place.	Process.	Production (brls.).		
				1938.	1939.	1940.
Schwarzheide	1937	Saxe	Fischer–Tropsch	(see Brabag group in Table V)		
Wanne Eickel	1939	Ruhr	Fischer–Tropsch	—	425,000	1,700,000
Bochum	1939	Ruhr	Fischer–Tropsch	—	425,000	1,700,000
Rauxel	1938	Ruhr	Fischer–Tropsch	340,000	425,000	1,700,000
Stercrade–Holten	1938	Ruhr	Fischer–Tropsch	255,000	637,500	850,000
Moers–Moerbeck	1936 and 1939	Lower Rhine	Fischer–Tropsch	255,000	765,000	765,000
Koln Neussen	1938	Cologne	Fischer–Tropsch	255,000	425,000	425,000
Dortmund	1939	Ruhr	Fischer–Tropsch	—	—	—
Deschowitz	1939	Upper Silesia	Fischer–Tropsch	—	212,500	425,000
Essen	1938–39	Ruhr	Carbonization and Fischer–Tropsch	212,500	425,000	1,870,000
Essen	1939	Ruhr		255,000	425,000	425,000
			I.H.P. Process.			
Recklinghausen	1936	Ruhr		850,000	1,062,500	1,275,000
Total				2,422,500	5,227,500	11,135,000
Total by I.G. Farbenindustrie				8,467,500	12,112,000	24,225,000
Total of both I.G. Farbenindustrie and Fischer–Tropsch				10,890,000	17,339,500	35,360,000

* Anon., *La Revue Petrolifère*, 1941, p. 237.

An advantage of the Fischer–Tropsch plants lies in the fact that they may be operated efficiently on a much smaller scale than the direct coal-hydrogenation plants operating on the Bergius process. Due to the possibility of decentralization of these plants, there is less danger from bombing, and even if a direct hit is scored, there is less loss of capacity.

In spite of the abundant potential supply of coal in Germany, Holland, Belgium, Northern France, Alsace, Lorraine, Poland, and Czechoslovakia, the aggregate production of which was of the order of 510 million tons per year (1938) figures, a factor limiting the maximum production capacity for war is doubtless man-power and alloy steels, which are scarce. In addition to furnishing the coal required for hydrogenation purposes, a further limitation imposed on extension of the coal-oil synthesis plants lies in the vastly increased coal requirements of the other war-production industries. According to previous data,[6] the amount of coal required to manufacture 1 ton of gasoline is 5 tons, and on this assumption the production of synthetic oil from coal will reach its approximate limits at around 42 million barrels (reached in 1941), although according to Lisle [7] the goal set for oil from this source has been placed at about 62 million barrels for 1942.

France has some small coal-hydrogenation units producing motor fuel at the rate of about 2,800,000 barrels a year—a top estimate—whereas Italy hydrogenates heavy, high sulphur Albanian crude oil to motor fuel at an annual rate of about 3,260,000 barrels. The data are given in Table VII.[8]

TABLE VII.

Synthetic Fuel Plants in Axis-dominated Countries.

	Synthetic Fuels (brls.).
France	
Bethune	425,000
Lievin	425,000
Harnes (Pas de Calais) (Fischer-Tropsch)	85,000
*Projected building (1939), 4 plants	1,955,000
Italy	
Bari	1,520,000
Leghorn	1,520,000
Valdarno, Tuscany	165,500
Total oil output by hydrogenation outside Germany	6,095,500

* It is not known whether these plans were carried through, because no information has been available on their status since June 1940.

Compressed Gases.

With the severe rationing of gasoline from petroleum and synthetic oils from coal sources, the use of alternate fuels has become necessary in many nations of the world. Compressed-fuel gases were developed for some years before the second World War. Low-pressure combustible gas for gasoline-engine propulsion started during the last war.

The low-pressure installation developed during the first World War is definitely a makeshift appliance, since the container for the gas is approximately as large as the vehicle on which it is installed. These containers[9] vary in size from 100 to 720 cubic feet, and provide for a range of from 15 to 25 miles per filling. The life of the fabric containers is about one year. Provisions are made for refuelling the gas-bags at regular gasoline filling-stations, where the gas connection is made from the gas mains in the city. Two hundred and fifty cubic feet of this gas is equivalent to one gallon of gasoline.

Some of the chief drawbacks to the system have been, first, the size of the balloon necessary to be effective in driving; second, the wind resistance of the fuel-bag, which is considerable at regular automobile speeds; third, the tendency of the bag to leak after two or three weeks with dilution of the gas with air; fourth, to collect snow in the winter-time, and, because of this added weight, the pressure is great enough to force gas into the engine too quickly and cause backfiring, with subsequent stalling; a fifth difficulty is the inadequate height of the bridges and under-passes to accommodate trucks with gas-bags, although bridges 13 feet high or more give no difficulty even for trucks. In July 1940, despite all drawbacks, there were eighty gas-filling stations in London, and a survey made by the British Commercial Gas Association has listed the gas-filling stations in each county.

Compressed gases under pressures varying from 75 to 5000 lb., depending on the type of gas, are more efficient in utilization than the low-pressure gases just discussed. However, here, too, there are drawbacks which reduce their efficiency for automobile use; the one factor of greatest importance is the extra weight which must be carried as the steel cylinder. Table VIII shows the weights of the compressed gases and values in relation to gasoline.

TABLE VIII.

*Compressed Gases in Relation to Gasoline.**

Gas.	Cylinder Weight (lb.).	Pressure (lb. per sq. in.).	Gas (lb.).	Gasoline Equivalent (U.S. gal.).
Propane-butane . .	117	75–150	100	18·0
Methane	115	3000–5000	28	4·56
City gas	155	3000	12·6	1·8

* Based on figures presented in *Petrol. Times*, 1939, **42**, 1073, 189.

In this field, as well as in the manufacture of synthetic fuel from coal, Germany has gone the farthest in its development. In 1939 she had six types of bottled gas on the market: city gas, coke-oven gas, methane, propane, butane, and Ruhrgasol. The facilities for the utilization of these gases include more than fifty filling-stations and about 75,000 vehicles using compressed gases of the various types.[10] The propane and butane are derived from the hydrogenation and Fischer–Tropsch plants.

Methane and city gas are more widely available than propane and butane. Natural gas-fields, sewage-disposal plants, and coal hydrogenation, coal carbonization, and oil refineries provide a considerable source of methane.

Italy has a small gas-field near Milan which has been developed for providing methane. Probably the most outstanding development of a fuel-gas source has been the utilization of methane derived from fermentation of city sewage. In Sweden as well as in other countries there has been a development in this line. The sewage gas [11] as it comes from the disposal plant is 64 per cent. methane and 35 per cent. carbon dioxide. This product is considered richer in caloric content than city gas. Purification of sewage gas takes place before it is used in motor-cars, although forty care belonging to the Road and Street Commission in Stockholm use the unpurified gas. This unpurified gas is about 58–78 per cent. as efficient as benzol.

The cylinders for the use of sewage gas are about 1·4 cu. ft. capacity, and two to four cylinders are necessary for each car. Each cylinder contains 212 cu. ft. of gas compressed to about 2000 lb. per square inch. The installations are the same as for city gas and methane. At the compressed gas-filling station the filling time is the same as for gasoline.

In utilizing the gases the changes in the car involve a spark advance, a change in the carburetter, and a system of valves for stepping down the gas pressure before entering the carburetter. Many cars are so arranged that a change from benzol use to the gas may take place at the instrument-board. The cost of conversion to the gas-burning vehicles ranges between $150 and $175, and the steel cylinders from $20 to $22.50 per cylinder. There are very few cities having the type of sewage systems necessary to obtain the methane for fuel, hence the development is not widespread.

The Soviet Union, France, and Denmark have developed compressed gaseous fuels also, and in general the type of apparatus used has been much the same as in other countries. A study [12] which was made in Russia in 1940 has shown that while preference was given to the development of gaseous fuels, little utilization has been made. Authorities in Russia have claimed that yearly utilization of coal gases in the Don River Basin alone would be equivalent to approximately 8½ million barrels of gasoline. In addition to this supply, the Soviet Union has rich deposits of natural gas in the Caucasus, Central Asia, the Far East, and other localities. Liquid gases are further available in large quantities as by-products from the petroleum industry.

According to latest news from Italy, methane gas, compressed to 300 atmospheres over-pressure, has been used to run a gas-fed railway engine of 120 horse-power between Rovigo and Venice. At present it is planned to place more of these locomotives in service.[13]

Gas-Producer Development.

Wood, coal, and other solid combustible materials have been used for a number of years as motor fuel in countries lacking in oil resources. There are a number of factors to consider in the widespread adaptation of gasogene (gas producer) vehicles, although the present war has left no choice in the matter. The use of gasogene-propelled motor vehicles has increased greatly in the past few years. In 1938 the European continent had about 9000 trucks and buses in operation, whereas 1941 indicated about 450,000—a fifty-fold increase. The tonnage of producer fuel substituted for about

8,329,000 barrels of gasoline. There are, generally speaking, three types of fuels used in the gasogene vehicles: wood, charcoal, and coal or their mixtures. In many countries wood and charcoal are the main types of fuel used, while in others the use of coal has become as widespread as that of wood.

Four countries—Germany, France, Sweden, and Italy—have been more responsible for the use and improvement of the gasogene vehicle than any of the others. For a number of years only hard woods, well dried, were suitable for the gasogene engine; however, Germany [14] developed technical improvements in the engine, so that wet and soft woods may now also be used. Filters made of glass wool remove the dust from the soft woods, and special heat exchangers have been installed to compensate for the heat loss due to utilizing wet woods. These improvements, it is reported, together with others, have brought the efficiency of wood-gas vehicles close to that of the diesel engine. A light-weight bus has been adapted for the use of wood-gas from these sources.

In order that fuel may be available for the 231,000 gas-generator vehicles in Germany, the German Motor Roads Fuel Company [15] has arranged for more service stations to supply "chipped wood." Twenty-two wood stations were to be opened between Berlin and Dresden in May 1941 in connection with the gasoline filling-stations. Germany required 2,891,000 tons of wood to propel the producer-gas vehicles during 1941, although the distribution arising from such widespread use of wood places a considerable burden on an already overtaxed transportation system in Germany.

With the widespread use of the wood-gas generator, the difficulty of increasing the supply of wood has become apparent, and consequently more attention has been given to the utilization of coal and peat. A problem which is still of great importance in all countries utilizing the gas generator is to invent an engine of the type that will run on all types of solid fuel. Up to the present no development of this nature has been brought out.

Sweden, another country in which development of the gas generator has made much progress, has used the generator vehicle for a number of years. At the outbreak of the war there was little difficulty in turning from gasoline to gas-generator vehicles. As in most countries, the majority of Sweden's gas-generator vehicles are trucks, but other vehicles have also been adapted. In January 1941 there were twenty different types of solid fuel-burning motor vehicles on the roads in Sweden. The type of fuel most desirable for these was considered to be birch wood. A series of tests were run on coal and wood in comparison with gasoline, and it was found that use of coal producer gas resulted in less lubricating-oil contamination than wood gas. Since lubricants are strictly rationed in Sweden, coal gas was considered more economical than wood gas for the generator vehicles. More trouble was encountered in winter driving with wood gas because of its higher water content [16] due to its freezing.

In France a somewhat different note is being sounded in the use of the wood-gas generator vehicle. For while France for a number of years encouraged the building and use of gas generators, many of her experts had predicted that too wide a use would cause a wood shortage. In June 1941 an order was issued forbidding the use of charcoal; the reason stated

was that wood supplies had fallen far below expectation. A report from Vichy, 13th February, 1942,[17] stated that the wood paving-blocks in the Place de la Concorde in Paris have been ripped out to use for fuel in wood-burning trucks, and that trees in the Bois de Boulogne had been cut down due to a timber shortage. The gas generators that were being built at that time were expected to be modified in order to burn other solid fuels.

Holland is another country cancelling permits for the use of the wood-gas-burner motor-cars.[18] There are approximately 1770 trucks in service using wood gas, but in future the manufacturers of the vehicles will be compelled to design the machine for burning peat, since this is available in Holland.

Italy in 1938 had 2200 wood-burning motor-buses and trucks, whereas in 1941 there were 5000 in operation. Italy is a country possessing very small forest reserves and less coal, hence the producer-gas-type motor vehicle has not alleviated the fuel shortage.

Denmark operated 11,656 wood-burning vehicles, according to *Foreign Commerce Weekly*; Norway, Belgium, and Finland, with 5563, 6023, and 10,000 gas-generator vehicles, respectively (see Table XI), were also finding a solution to their fuel situation by this means, since they had sufficient forests to provide the gas-generator type of fuel.

Throughout the occupied countries in Europe and those affected by the blockade the effect of the oil shortage has been to force the use of substitutes, and in many instances these substitutes have been wood or coal-producer-gas vehicles. Switzerland and Sweden, two of the four neutrals left on the continent of Europe, have felt the pinch of fuel scarcity to practically the same degree as the occupied countries. Switzerland only licences the gasogene vehicles considered vitally necessary.

Embattled Russia, in spite of her vast oil resources, has also turned to the gas-generator vehicle for motive power.[19] Tractors and trucks in the Soviet Union[20] have had considerable development, since many of the agricultural centres are far from liquid fuel supplies, but in or near the forests and peat-beds. The design of the vehicles has been in some instances for charcoal and anthracite, and in others, especially the heavy trucks, for peat and bituminous coal. Other tractors with producer gas units

TABLE XI.

Producer Gas (Gasogene) Vehicles.

Country.	Number of Vehicles, 1941.
Germany	231,000
France	57,000
Denmark	11,656
Finland	10,000 (1940)
Belgium	6,023
Norway	5,563
Italy	5,000
Holland	1,770
Sweden	75,000
Russia	40,000 (1940)
Total	443,012

have been tried on straw briquettes, but up to the time the article from which this information was taken was written no practicable results had been achieved.

In France and Denmark a number of boats have been adapted to the use of charcoal or wood. Germany is reported to be operating 1000 boats, with 1400 to be in use early in 1942.

Table XI shows the number of vehicles in use in the various countries that have had to adopt solid producer-gas fuels rather than liquids to provide transportation.

The fifty-fold increase in producer-gas-propelled motor vehicles during the last three years has been confined to land vehicles and boats. It is interesting to note to what extremities some countries are being driven in the use of substitute fuels, as an Associated Press report out of Rome, 16th December, 1940, said:

ITALIAN PLANE MAKES FLIGHT ON CHARCOAL GAS

Rome, Dec. 16—(AP)—A flight by a charcoal-burning airplane, said to have been the first ever made, was reported today by the newspaper *Il Messaggero*.

The newspaper said the flight was made by Constantino Mazza in a Breda plane powered by a "gasogene" motor yesterday over Taliedo Airfield, near Milan. A test flight from Milan to Rome is planned next.

A special apparatus said to have supplanted the plane's gasoline tanks was described as weighing 176 pounds—99 pounds of charcoal and a low-temperature furnace to convert the charcoal into gas.

Power Alcohol.

Power alcohol consisting of both methyl and ethyl alcohol was fostered by a number of countries short of petroleum in an endeavour to make themselves self-sufficient from their own natural resources, not alone for peace-time, but for war. Methyl or wood alcohol is derived from distillation of wood or sulphite pulp from paper-making, and hydrogenation of carbon monoxide. The raw materials used for ethyl alcohol production are mainly foodstuffs, such as sugar, beet, and potatoes. It became a question of balance as to whether power alcohol is more important than food in the war economy.

It has been generally conceded that the alcohol industries were kept going in peace-time for the primary purpose of furnishing sufficient ethyl alcohol for the munitions industries in case of war. The events of the past three years or so have borne out this idea. It was reported in 1939 that Germany reduced the ethyl alcohol content of motor fuel from 8·2 to 2·3 per cent., and discouraged the use of methanol entirely.[21] It appears as if ethyl alcohol will also be eliminated due to food shortage.

The occupied countries of Europe are using alcohol as a motor fuel, although a general curtailment has been evident since 1936 for technical reasons and because of food shortages.[22,23]

In 1941 France was utilizing grape alcohol[24] as one of the substitutes for gasoline. The alcohol was distilled from the pulp after the wine was pressed, and oil was obtained from the grape-seed. Grapes have also been the source of much of Spain's motor fuel. The Government instituted the use of alcohol in order to utilize the great surplus of grapes.

The Swiss Government has designed a plant for the purpose of distilling wood which will produce 16,000 tons yearly of methyl alcohol and 10,000

tons of "alkaeton," a motor-fuel substitute. Sweden also utilizes wood alcohol and some turpentine. These products are derivatives of wood pulp by special processes. It has been estimated that wood alcohol could be produced to the extent of 290,000 barrels per year in existing plants.

Table XII shows the extent of alcohol production in the principal European countries for 1939; for other countries the figures are for 1941 wherever possible.

TABLE XII.

Power Alcohol Production (Brls.).

Country.	1939.*
France	1,600,000
Germany	4,000,000
Italy	350,000
Poland	100,000
Hungary	80,000
Lithuania	50,000
Sweden	290,000 (1941)
Switzerland	195,000 (1941)
Total for Axis Europe, based on 1939 figures	6,480,000

* V. R. Garfias and R. V. Whetsel, *A.I.M.E. Trans., Petrol. Div.*, 1941, **142**, 246.

Many sources of power alcohol have been exploited, but perhaps the most unique of all is the one reported in Sweden, where a baker adapted his ovens so that the alcohol produced during baking was condensed and used as a motor fuel. His fleet of thirty trucks are fuelled by means of the alcohol extracted from the steam of baking bread.[25]

Japan.

The Asiatic part of the Axis—namely, Japan—has through the years endeavoured to increase her fuel supplies by means of discovery, research, and conquest. Japan's primary sources are petroleum, coal hydrogenation, coal carbonization, and oil shale. Fuel substitutes include alcohol, wood-burning and compressed-gas vehicles, and other miscellaneous fuels such as sardine oil and garbage.

Japan's status in oil and its substitutes prior to the outbreak of the war with the United States, Britain and Holland and the conquest of the Netherlands East Indies, British Borneo, and Burma is indicated in Table XIII.

Various authors have given the synthetic fuel production expected under Japan's Five- and Seven-Year Plans. B. O. Lisle [26] has estimated 22,180,000 barrels, H. S. Norman [27] reports 16 million to 18 million barrels for this production, and *Business Week* [28] quoted 7 million to 9 million barrels. Due to the preceding estimates being based on *plans* for substitute fuel production in Japan and the considerable doubt of their having been carried out, it was thought advisable to use in Table XIII the lower figure of 4 million barrels of synthetic oils, as reported in *World Petroleum* of January 1942.

The foreign crude oil and products therefrom given in Table XIII are direct shipments to Japan. To give an estimate of the volume transhipped

TABLE XIII.

Oil Economy in Japan.

Source of Oil.	Barrels.
Japan	
Crude petroleum (includes Formosa and part of Sakhalin)	3,800,000 (1941)
Synthetic oils (coal and carbon monoxide hydrogenation)	4,000,000 (1940)
Manchurian shale oils	3,000,000 (1940)
Motor alcohol	2,396,000 (1939)
Total oil indigenous to Japan	13,196,000
Foreign oil imports to Japan	
United States	24,889,000 (1940)
Netherlands East Indies	7,000,000 (1940)
Iran	1,000,000 (1940)
Mexico	1,600,000 (1940)
Total imports	34,489,000

through neutral ports was not possible, as the data are not available. Just how much oil Japan had in storage on 7th December, 1941 is not clear, although it is considered "large." The oil-refining capacity of Japan in 1941 was reported to be about 64,000 barrels a day in twenty-eight refineries. The U.S.A. has a daily refining capacity of over 4 million barrels of crude oil.

The consumption rate of petroleum and products for civilian use in Japan during 1940 was about 26 million barrels, and for military and navy needs about 14 million barrels, or a total of 40 million barrels peace-time needs. At the present war rate of oil consumption Japan is probably using more than twice the latter volume, despite drastic civilian curtailment.

The Netherlands East Indies in 1941 produced about 62 million barrels of crude oil, while British Borneo yielded 9½ million barrels. The oil-fields and refineries (in a highly damaged state) are in the hands of the Japanese.

According to Kessler,[29] oil installations in the Dutch East Indies valued at $500 million were developed over a period of fifty years and thoroughly destroyed before Japanese occupation. Many of the oil-wells were plugged with cement so that a reopening of the well could not be accomplished without completely redrilling. In the destruction of Tarakan, Balik Papan, and Palembang alone, 88 per cent. of the total oil available in the East Indies was cut off by the Dutch. Only at Tarakan, where the crude needs no special refining, could redrilling give the Japanese oil they need. According to the most authoritative statements from Batavia, the time required to obtain the necessary drilling equipment, pipe-lines, pumps, tanks, special refinery fabricated materials, fine instruments, etc., and actual drilling to production again would require from 18 to 24 months.

Burma Oil Production.

Burma in 1941 produced 7,762,000 barrels of crude oil with several operating refineries. A thorough "scorched earth" policy was carried out by the British, which is borne out by a Calcutta, 7th May, dispatch,[30] as follows:

"It will take the Japanese ten years to restore the blasted Burma oil-fields to capacity production, American drillers said today on arrival here from Yenangyaung and Chauk, where they helped demolish more than 4000 wells in eight days."

"'We left behind nothing the Japanese could use,' said G. Whitley, of Batson, Tex., an employee of Burmah Oil Company, who helped with the Yenangyaung destruction. 'We destroyed 3021 wells with explosives which dropped the pipes to the bottom and by firing the free-flowing wells.'

"He said they also fired thousands of barrels of oil stored in tanks, then tore down tank and derrick superstructures, and cut up the machinery with torches.

"The demolition was carried out between 10th and 18th April, but most of the work was packed into the last two days after British authorities ordered total scorched-earth destruction.

"Mr. Whitley said it would take at least ten years to get the fields going to capacity, and G. W. Akers, Long Beach, Calif., another Burmah employee, said it would take the invaders months to realize any flow, even if they got equipment promptly."

The 1941 production of the areas now in Japanese hands is shown in Table XIV.

TABLE XIV.

Area.	1941 Production (brls.).
Dutch East Indies . . .	63,130,000
British Borneo	6,864,000
Burma	7,762,000
	76,756,000

These oil-producing areas in the hands of the Japanese have been subjected to a "scorched-earth" programme, and the oil from these sources is unavailable for some time to come. On this basis the substitute fuel production assumes a more important place in Japan's fuel economy than the outputs shown in Table XIII would warrant, since this production is indigenous to Japan.

The substitutes in use in Japan at the present time are: (1) gas generated from charcoal, wood, coalite, and acetylene from calcium carbide, and (2) natural gas, petroleum gas, and methane from garbage, etc. Natural and compressed gas is used only in the area of its production because of a lack of steel containers for further distribution. The oil synthesis programme [31] (Fischer–Tropsch and Bergius) has been slowed down considerably by the lack of steel and alloys both in Germany and Japan, and the absence of suitable coals for hydrogenation purposes in Japan.

Charcoal and wood are the only substitutes that have received particular encouragement from the Government, and even the charcoal substitutes are limited for motor fuel use, since industrial and domestic demands far exceed the production. In addition to the fuel limitations, the manufacture of the gas generators has also been curtailed due to a steel and labour shortage.

Alcohol still remains as a source of motor fuel, and according to laws reported enacted in Japan [32] all oil companies were required to maintain emergency reserves of alcohol equivalent to at least 20 per cent. of the gasoline on hand for six months' sales.

The tanker fleet in Japan, which is now of the utmost importance in fuel transport to the war theatre in the Far East, is reported to have consisted of forty-seven vessels (in 1940), the majority of which were the

largest and fastest type (19 knots per hour in contrast to 10–12 knots), with a gross tonnage of over 440,000 tons, and probably has been augmented during the past year. The Japanese law [33] required that all companies operating in the Japanese market carry a six months' supply of petroleum products. The Government provided storage tanks for lease to the companies and covered any losses that might occur from evaporation or catastrophe. In addition to the commercial petroleum stocks on hand, the army and navy were known to have accumulated "large" inventories which were stored underground for protection.[34]

Conclusion.

Many types of motor fuels and substitutes are being used by the Axis Powers. There is a decided stringency in the allowable use of even substitute fuels, due to lack of raw materials, manufacturing facilities, and man-power for their preparation. The relatively poor quality of the Axis fuels has curtailed the manœuvrability of their automotive transportation, including airplanes.

The successful conclusion of this war will be based largely on the superior quality and quantity of the motor fuels available to the United Nations in unlimited volume.

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THE VALUE AND ACCURACY OF FIELD MEASUREMENTS.*

By C. J. May and R. Pike.

The Uses of Production Data.

Modern oilfield exploitation calls for at least a certain minimal scientific background—the absolute minimum would be provided by a purely short-term approach to the problem. Here a study of surface and sub-surface geology would be used, broadly speaking, to minimize the number of dry holes drilled, but once a well was completed it would be produced and treated as an individual and in accordance with the dictates of short-term economic factors only.

Even with such a development policy both the geologist and the operating engineer are progressively receiving more and more assistance from physical or chemical measurements of one kind or another. Bottom-hole pressures, production data, analyses of oils and waters, and so on, are increasingly used both as evidence of sand continuity or discontinuity, and also in determining completion repairs and beaning programmes.

However, the importance of physical data is very much more marked when we come to consider long-term development policies—that is to say, the problem of making the maximum profit in the long run and not merely a sufficient profit in each successive year. There are then, broadly speaking, three additional factors to be considered :—

1. It is not merely desirable that each individual well should pay off and show a profit ; we must aim at drilling the absolute minimum number of wells which will produce all the profitable oil.
2. If two or more wells are mutually interfering, then these wells should be produced to the best advantage as a group, and not as individuals.
3. After the field has been exhausted by primary methods, we should be in a position to consider the possibilities of secondary methods of production.

It would take too long to discuss in any detail the methods that can be used in solving such problems, but we may mention, for example, the plotting and extrapolation of production data ; the estimation of the effects of interference ; the determination of the effects of various producing methods on water and gas encroachment, and on the ultimate percentage recovery ; the estimation of the effectiveness of gas drive, etc. It is very evident that if such work is to be tackled at all, the first essential is a sufficiency of reasonably accurate data on oil, gas, and water productions, surface and sub-surface pressures, and so on. We immediately come up against the question of what constitutes reasonable accuracy.

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* Paper read at a Meeting of the Institute of Petroleum, Trinidad Branch.

The Desirable Order of Accuracy.

It has, of course, first to be recognized that no amount of care and expense can guarantee 100 per cent. accuracy. They can only reduce the magnitude of error without eliminating them entirely. Further, it is a waste of money and energy to strive after an unnecessarily high order of accuracy—the permissible range of error depends entirely on the purpose for which the data are to be used.

The first question to be decided, therefore, is whether and to what extent we are justified in attempting the long-term analysis of production data.

It might be suggested that sub-surface conditions in Trinidad are so complex that it will always be impossible to generalize, and that we are therefore not justified in attempting anything other than to increase and maintain the efficiency of short-term operations. For this purpose a rather limited amount of data of no very high order of accuracy might be sufficient. In any case, deficiencies in the data will readily reveal themselves from time to time, and accuracy will tend automatically to follow the law of short-term supply and demand. Regarded from this point of view only, the records of most oil companies are probably fairly adequate, and an investigation of errors would appear to be of little more than academic interest.

However, the amount of oil still to be recovered and the amount of money to be spent in the process are considerable, and if detailed analysis of field data can increase the first or reduce the second by only a few per cent. as compared with more empirical methods, a fairly considerable expenditure would be justified. From this point of view there are two or three important points to be considered.

The amount and accuracy of the data collected doubtless vary from one company to another, but even in the case of those companies which pay the greatest attention to this subject, it is probable that some of the complexities of the long-term production problems are more apparent than real and would be resolved by a still further increase in the standard of field measurements both in quantity and in quality.

This is particularly true since the long-term value of adequate and accurate data is not always immediately apparent. Frequently it is only after the lapse of some years that accumulated data can be studied in proper perspective, and the errors and omissions of perhaps ten years ago begin to be important.

In this connection it should also be remembered that the science of production engineering is a comparatively new one. Our ideas as to the behaviour of fluids in the reservoir, for example, have been revolutionized during the last ten years.

There seems every prospect that the near future will see the practical application of what are at present little more than academic theories, and these applications will certainly call for the use of accurate data accumulated in the past.

There seems, therefore, to be every justification for accumulating more data and for aiming at a higher order of accuracy than appears to be necessary for immediate practical purposes. Furthermore, the value of any data, however accurate, is very greatly diminished if we have no idea as to their

probable error—this is particularly true in the circumstances with which we are concerned, where we are working to a large extent with an inadequate basis of established theory.

Unless we have such an idea, we shall always be coming up against the question of whether apparent variations are significant or whether they may merely be due to error.

In order to establish what the maximum errors may be, and to ensure that any specified degree of accuracy is continuously achieved, it is necessary that all the possible sources of error should be investigated in detail, and that methods, instruments, and records should be constantly checked.

If detailed and comprehensive records are aimed at, the supervision necessary to guarantee *any* reasonable degree of accuracy is an expensive item, and one to which insufficient attention is frequently paid. It should, however, be recognized that the mere fact of carrying out a detailed study of accuracy will automatically eliminate many of the grosser errors. To take a simple example: if we wish to know what range of errors is likely to be introduced into gas measurements by variations in gas gravity, we must carry out a detailed survey over the field, and we can then use the information so obtained to eliminate errors due to incorrect estimation of gas densities.

There will, of course, always be a residue of errors due to the instruments or methods used, but these can generally be comparatively easily estimated, and the question of whether it is worth while to try to reduce them can be dealt with as a separate problem.

In this paper we do not attempt to lay down absolute limits of permissible error. We shall enumerate and briefly discuss some of the more obvious sources of error which should be the object of investigation on any field where attempts are being made at detailed analysis of field data.

Types of Error.

In discussing the accuracy of methods, there is a common and natural tendency to assume that over a period of time errors can be largely "averaged out," and that their absolute value is therefore not of great importance. This assumption is sufficiently true in some cases to make it a dangerous generalization. It has to be remembered that there are many different types of error, and also that data are used for many different types of calculations, and it is by no means generally true that the errors of individual measurements are unimportant.

Of the different types of error we may refer specifically to four :—

1. Random errors vary in magnitude, but are equally likely to occur in either direction. These are the most likely to average out, and are therefore probably the least important.

We have to consider, however, that in oilfield work we do not often measure exactly the same quantity more than once. A good deal of our averaging is done by smoothing curves—for example, drawing a production-time curve and extrapolating to estimate the ultimate production of a well. But just as runs of good or bad luck at cards or roulette, for example, are not uncommon, so there will be periods when for a consecutive series of readings the errors all tend to be in one

direction. If such a run occurs at a critical point in a curve it may seriously upset extrapolation, or lead to the assumption of some non-existent production anomaly.

2. Constant systematic errors are errors which always have the same value in the same direction. A simple example is that of an error in tank calibration which means that all measurements of oil made by gauging in that particular tank are affected by a constant percentage error.

For the purpose of some types of calculations, errors of this kind may not be very important—if, for example, we are only concerned with the percentage decline of production of a well which is always gauged in the same tank. Also in taking an overall field average, the systematic errors of each installation may become, in effect, random errors. But if we wish to compare the actual productions of two wells which are gauged in different tanks, it is clear that systematic calibration errors may seriously affect our conclusions.

Constant systematic errors are liable to occur in any type of measurement, and are important from two points of view. Firstly, for a given mechanical installation and method of measurement they cannot be averaged out; and secondly, they are generally much more difficult to detect than are random errors.

3. Variable systematic errors are errors arising from the method or instruments used which have a definite value at a particular time but are liable to change either continuously or abruptly during the course of a series of measurements.

Again, to take a simple example. If the orifice plate of a gas-metering system slowly erodes or cuts out, then, so far as any one measurement is concerned, there will be a definite error due to the oversized orifice; in subsequent measurements the error will always be in the same direction, but will be continually increasing.

It is clear that if they are large, such errors as this can seriously affect the shape of curves in which the measurements are incorporated, and hence upset extrapolation or deductions drawn from comparisons between curves.

These errors, again, cannot in general be averaged out, and are difficult to detect and eliminate, unless a complete and rigid system of frequent inspection and calibration, etc., is enforceed.

4. Finally, there are the gross errors due to accident or carelessness which occasionally occur even in the most carefully conducted investigations. The magnitude of such errors is generally outside the normal range of random errors, and they can frequently be spotted by inspection if there is a sufficient basis of theory to work on. In a good deal of our work, however, we are not sufficiently sure of our theory to know whether an apparently large discrepancy may not be significant. Furthermore, much of our data is collected by employees who can scarcely be classed as scientific observers. They may continue to make the same gross errors over a long series of measurements (so that these errors almost become systematic), and will frequently tend to return the sort of answer they think is expected rather than the one they have actually observed.

In field measurements, unless there is very adequate supervision, gross errors may outweigh all others in importance and make it impossible to carry out any but the roughest of calculations.

Sources of Error.

The actual accuracy of a multitude of field measurements warrants a much more detailed consideration than is possible or desirable in this paper, but it is hoped that the several points which will follow will assist the discussion which is the main object of this meeting.

The measurements with which petroleum engineering is most concerned are those of volumes of oil, volumes of gas, and various types of pressures. The sources of errors in each of these groups are somewhat different in origin, and points will be made under these separate headings.

Oil Volumes.

Tank-dipping is the most common method of measuring quantities of oil. Whether gauge-rods or tapes are used the main sources of error are the same, although there may be individual preferences for either measuring device.

Errors are introduced by approximating the position of the oil-mark to the nearest prescribed fraction of a foot, dipping with an oblique gauge-rod or tape, adjusting for stable foam, and dipping from B. S. on tank bottoms.

Any dips must, of course, be converted into volumes by the use of calibration figures, and while in small new tanks without deadwood an error in calibration may be constant for a particular tank, for tanks *with* deadwood, and for older tanks which may have suffered from heavy handling, the percentage error for various depths of oil may be very different.

Modern tanks of small capacity are supplied with makers' calibrations, which are issued as standard, but actual checking of their figures may show discrepancies. The accurate strapping of tanks is not a very simple procedure, and due consideration must be given to the accuracy of the method used before any true comparison can be made.

It is quite common practice to test individual wells in two separate tanks at intervals and with, say, a + 5 per cent. calibration error in one tank and a − 5 per cent. error in the second, variations of less than 1 per cent. in oil volumes prior to the time the discrepancy was discovered would not be significant.

In the type of analysis of production data which should be possible, a rapid but true change of 10 per cent. in the production of an individual well might be very significant.

The calculation of oil volumes must, in field practices, often be combined with the determination of volumes of both free and suspended water. While the former is subject to the same type of dipping errors as the oil, the latter is very much affected by errors of sampling. On this point it will suffice to say here that poor methods of sampling, especially the use of non-standard technique, may introduce errors which, although possibly unimportant from the point of view of bulk oil receipts, will seriously limit the application of data either to routine problems or pure research.

Although there is a possibly small random error in the actual process of

dipping oil, the evidence is that tanks are commonly gauged to contain a greater height of oil than is actually the case.

For this type of measurement we must rely largely on field employees who are not all as reliable as might be desired—consequently the accuracy of gauging is very often impaired by gross errors. The only method of reducing the number of such errors to a reasonable minimum is by systematic and continuous checking, and this can be simplified by organizing some form of instruction for the employees.

Gas Volumes.

The orifice meter is by far the most common method used to obtain gas volumes, and a brief survey of the errors involved in such measurement will illustrate both random and systematic errors as well as a plentiful source of gross errors.

The random errors occur in the mechanical accuracy of the meter used (some meters have a tolerance of $\pm$ 1 per cent.) and the reading of the static or differential outline on the chart.

The orifice meter method allows a large number of systematic errors to affect the accuracy of results obtained, and unless these sources are carefully checked, gross errors may result.

A simple source of such an error is in the diameter of the orifice plate, and the accuracy of this will depend on the reliability of the machinist as well as on the amount of erosion after installation. Large percentage errors are not easy to prevent in the smaller orifices.

Faulty zeroing of either the static or differential pen may introduce either constant or variable systematic errors.

It is also necessary to have a reasonable idea of the variations in the flowing temperature of the gas and the causes of the changes in temperature might warrant a close study. The temperature factors (for adjusting coefficients based on 60° F.), for flowing temperatures of 70° and 100° F. are 0·9905 and 0·9636 respectively, which for an average of 85° F. represents a range of about $\pm$ 1·4 per cent.

Similar comments will apply to the application of a flowing gravity factor, although the range is considerably greater. A range of gravities of 0·58 to 0·72 has been obtained for local gases separated at 250 lb./sq. inch, and it is possible that more gases will be found to go outside this range. The factors for the gravities mentioned are 1·3131 and 1·1785 and for an average of 0·65, this is a range from +6 per cent. to — 5 per cent.

Any attempt to average conditions in this way will introduce systematic errors which will not necessarily stay constant over a period of time.

The supercompressibility factors for the various gravities will vary with both gravity and temperature, and an average condition must be struck. This, of course, will introduce more errors, and these are likely to be large if the full range is not explored.

In normal field operations it is common practice to use published coefficients, and if various sets are compared, it will be seen that there are important differences in the values for basic orifice coefficients. A range of differences from + 2 per cent. to — 1 per cent. has been found in comparing two accepted tabulations.

Gross errors in gas metering can be very frequent, and usually result from failure to service either the primary or secondary elements sufficiently often. The use of a non-standard metering manifold may introduce flow disturbing apparatus too near to the plate, and gross inaccuracies may result.

Gas chart computation is an operation which may introduce errors again of the three general types, although gross errors may be more common.

Average flowing wells in Trinidad do not give gas charts which lend themselves readily to visual computation. Considerable advantage can be obtained by utilizing at least 50 per cent. of the scale of the chart, and all-round efficiency in computation can be improved by using the correct planimeter. Whenever possible it should be preferable to eliminate unscientific estimation.

Pressure Instruments.

In pressure instrument data the three general types of error are again found. There is the normal random error of observation, which will depend on the scale of the instrument. It is clearly not generally good practice to use a 3000-lb. gauge to measure a pressure of a few hundred pounds.

The constant and variable systematic errors of calibration, etc., are to a large extent dependent on the amount and quality of the instrument servicing.

Gross errors are introduced by manhandling of the instrument, as well as the possible inability of the operator to appreciate small intermediate scales. Occasional freak errors do occur, and may be caused by trapped water between a cracked glass and the face of the instrument, for example.

The same general comments will apply to sub-surface pressure records.

Data of the three groups outlined form the basis of the simplest analysis of individual or group well behaviour, but for the purpose of correlation some consideration must be given to the choke or bean size.

Flow Beans.

Various types of bean are used, and while the effective orifice diameter is initially subject to the usual errors of machining, some " cut " and/or erode faster than others.

A fast cutting bean is naturally located quickly, but very slow erosion (which has been observed over a considerable period of time) may cause the records of a declining well to show a more or less constant, or even slowly increasing rate of production. Thus close checking of bean diameters is of primary importance, if any use is to be made of decline curve analyses.

In conclusion, while there are considerable grounds for discussion as to the amount and quality of data that form adequate production records, there is little doubt that we should collect data in excess of our immediate requirements, and that the uses to which the data can be put are set by the limits of accuracy of the data.

We should not draw inferences from variations within the known zone of error, nor should we seriously restrict the uses to which the data can be put by making the zone of error too extensive.

Some of the errors mentioned above may appear to be small in magnitude, but the cumulative effect of a number of small systematic errors can be

considerable. In any case, as we have already pointed out, without a detailed survey of the methods used on any particular field, coupled with constant supervision, there can be no guarantee of any specified limits of error.

Our comments have deliberately been kept brief, and amount to no more than a sort of agenda for discussion which we would suggest might reasonably be opened by considering the views of members on the amount of field data which it is desirable to accumulate, and might pass from there to a consideration of methods, equipment, and accuracy.

GAMMA-RAY WELL-LOGGING IN TRINIDAD.*

By Glenn M. Conklin.

Well-logging by Radioactivity, or Gamma-Ray Well-Logging, as it is usually called, involves the process of measuring the gamma-ray activity in the aggregate of the material adjacent to a bore-hole and plotting a graph of the gamma-ray intensity *versus* depth. This type of logging was developed rationally to fulfil the great need of the oil industry for a method of securing accurate knowledge of the lithology of the strata cased off before the advent of electrical logging. Because the gamma-ray unit works equally well in holes with several strings of casing or in open holes, it is suited admirably to the purpose of locating cased-off oil-sands or horizons for identification and correlation. In order to discuss this type of logging it is necessary to touch briefly upon the phenomenon of radioactivity, to describe the methods of measurement, and to enumerate the possible uses of the gamma-ray log.

Radioactivity is the spontaneous disintegration of atoms which, by the emission or the release of alpha-rays (helium nuclei) and beta-rays (electrons), causes the parent element to change its physical characteristics, and hence its place in the periodic table. Concurrently with the alpha- and beta-rays are emitted electro-magnetic radiations called gamma-rays, which are much more penetrating than either of the other two. Because these gamma-rays will penetrate the several inches of iron necessary to successful logging, they are the only ones of importance to us. Of the several known radio-elements, uranium, actina-uranium, and thorium are the parent elements of three highly radioactive series. (The well-known radium is an intermediate member of the uranium series.) These three parent elements disintegrate into at least forty distinctive members of the radio-active series, with non-radioactive lead as the end-point in all three transitions. Of the other elements known to be slightly radioactive, potassium is the most widely distributed, and no doubt contributes considerably to the over-all gamma-ray effect.

Table I.

Relative Radioactivity of Sedimentary Rocks.

Formation.	Grams of Radium Equivalent per Gram of Rock $\times 10^{-12}$.
Black shales	25·0–60·0
Grey shales	15·0–25·0
Sandy shales	5·0–15·0
Sandstones	0·5– 5·0
Salt and coal	Less than 2·0
Volcanic ash	15·0–25·0
Potash rock	50·0–70·0

* Paper read at Meeting of Institute of Petroleum at Apex Club, Fyzabad, on Friday, 27th March, 1942.

Extensive laboratory experiments have shown that radioactive materials in one form or another are found in all substances. Fortunately, sedimentary rocks in general have radioactive properties which are characteristic to each particular substance, and in most areas well-defined strata have definite "radioactive breaks" that may be easily identified. Table I gives a few comparisons of the relative radioactivity of sedimentary rocks expressed in terms of the radium equivalent per gram. These samples are taken from all over the world. In the case of Trinidad, measurements were made of eight samples from the oilfield district with the following results in Table II :—

TABLE II.

Radioactivity of Cores from Trinidad.

Sample.	Grams of Radium Equivalent per Gram of Rock $\times 10^{-12}$.
Forest sand	2·0
„ clay	7·1
Cruse sand	3·7
„ clay	8·4
Mayaro sand	4·1
„ clay	10·5
Montserrat sand	5·4
„ clay	10·1

More than likely the variation in the values obtained in the cases of the four sands are caused by the clay contamination of the sand, which in Trinidad is rarely pure. In most instances a relatively pure sand has a radioactivity of 2×10^{-12} grams of radium per gram of rock.

MEASUREMENTS.

Since it has been proved that sedimentary rocks have radioactive properties that are identified fairly easily, and in many cases are much more continuous than fossils or the parameters used in electrical logging, it was necessary only to devise a means of measuring the radioactive properties of the strata without bringing cores to the surface for laboratory study. Of the several ways to measure the gamma-ray intensity of the rocks adjacent to the drill-hole, the ionization chamber is the most satisfactory. This method is not new. Fundamentally, it consists of two electrodes immersed in an inert gas under pressure and connected externally to a circuit containing batteries. When gamma-rays or any other radiation enter the chamber and ionize the gas, a current flows in the circuit which is directly proportional to the ionization or the intensity of the radiation. For practical purposes, and for convenience of operation, the ionization chamber used in gamma-ray well-logging is enclosed in a cylinder, the outside diameter of which is $3\frac{1}{8}$ inches for the small instrument and $4\frac{1}{8}$ inches for the large one. Also contained in the same cylinder is a very high-gain amplifier with appropriate batteries. The over-all length of the tool is about 9 feet, and when in operation is hermetically sealed and attached to a single-conductor cable $\frac{3}{8}$ inch in diameter. This cable is covered with two layers of steel wire

wound in opposite directions to prevent twisting. The average stretch is about 1 foot for the first 4000 feet.

At the surface this cable is wound on the drum of a hydraulically operated winch with a 12,000-foot capacity and capable of maintaining constant speeds of from 100 feet per hour to about 20,000 feet her hour. This winch is mounted on a 1½-ton truck, together with an Onan AC generator of 110 volts 1500 watts rating; also on the winch truck are suitable indicators for cable speed, depth of instrument in the well, tension on the cable, and other pertinent information.

The purpose of the winch truck is to raise or lower the sub-surface tool in the well and to supply power for the amplifiers, lights, and other electrical apparatus. The actual log is made in a recording truck containing amplifiers and a Speedomax recording unit which, by means of a potentiometric pen, draws a graph of the variation of gamma-ray intensity of the strata being traversed *versus* depth. Also in the recording truck are depth indicator, an oscilloscope for studying the action of the various electrical circuits, and very complete testing equipment. Once the preliminary adjustments in scale values and logging speed are made, the entire operation of the equipment is automatic.

In order to ensure dependable depth measurements, a measuring wheel 10 feet in circumference is placed at the surface of the drill-hole. This wheel guides the cable and drives a master Selsyn motor, which in turn actuates two other Selsyns, one in the winch truck and one in the recording truck. In this way the winch operator and the recording engineer know at a glance the absolute depth of the instrument in the well. A remote control-weight indicator is placed under the measuring wheel at the well in such a way that the winch operator is aware at all times of the tension on the cable. Because of the extreme sensitivity of the device, it is possible to determine the bottom of the well very accurately and to observe in the hole any irregularities, such as semi-collapsed casing on other obstructions.

A slightly technical explanation of the process may be stated rather simply. As the ionization chamber passes the various strata, usually coming out of the hole at a speed 1500 feet per hour, the varying intensity of the gamma radiation causes variations in the ionization of the argon gas in the chamber, and hence variations in the current in the external circuit of which the electrodes in the ionization chamber are a part. This current is a varying direct current in the order of 10^{-13} amperes. Since it is too small to measure directly, and since it is direct current, a specially designed device is used to compare the IR drop of this current through a resistor of 10^{11} ohms to the IR drop through a resistor of 10 ohms. By automatically maintaining the voltage drop across the 10-ohm resistor equal to the voltage drop across the 10^{11} ohm resistor, it is possible to work with a measurable current which, because of the potentiometric characteristics of the circuit, is a linear equivalent to the ionization current. In order to avoid using direct-current amplifiers, this variation is changed into alternating-current equivalents which are sent to the surface, and by means of appropriate filters are changed back to the proper form. The final current in the recording truck is filtered and amplified and passed to the Speedomax recorder, which automatically draws the curve with ink on a continuous strip of graph paper.

The Log.

The gamma-ray log resembles the self-potential curve of the electrical log, in that sharp breaks are indicated at the contact of sands and clays or any other contact at which the radioactivity undergoes a change. The gamma-ray log indicates the sand-clay contact, it also shows considerable detail in the clay and indicates the contact between the silt and the clay. This differentiation has considerable value in Trinidad, because the radioactivity of the strata seems to be proportional to the percentage of sand or clay present. Thus a bed that is 50 per cent. clay and 50 per cent. sand gives half as much relative deflection on the log as a bed of pure clay. This enables the operator to estimate the clay content of the sands and hence the porosity.

The only effect of casing on the log is an over-all absorption of the gamma-rays, which effect can be overcome by raising the gain of the amplifiers at the surface. When an additional string of casing is encountered in the well, the pen of the recording unit shifts to the left on the log an amount equal to the absorbing effect of the casing. In order to compensate for this condition and to make the axis of the log essentially a vertical line, the recording pen is returned to its original position on the log and the gain of the amplifiers raised to a point to make the amplitude constant throughout the entire log.

Observations and Results.

Radioactivity well-logging has supplied considerable information in the old wells drilled and cased many years ago without the benefit of accurate coring or of electrical logging. Sampling at best was casual and often inaccurate, and in many cases sample lag was ignored entirely.

1. A gamma-ray log resembles the self-potential curve of an electrical log, except that more detail is shown in the silts and clays; and particularly, silts, clays, and sands are differentiated.

2. Definite correlation was established in certain areas by locating the base of the Forest Clay and other markers. It was found that the Forest Clay and the Intermediate Clay both have radioactive properties which make them easily recognizable over the oilfield district of Trinidad. In this area many fault problems were solved, and relatively complete geological information was obtained which was impossible to get in any other way.

3. The sands are identified easily on the gamma-ray logs, so that intelligent perforation programmes based on information from nearby wells can be outlined. A number of cased off sands in the old wells have been perforated with excellent results in most cases.

4. By comparing sands logged with the old perforations, it has been possible to rework some of the wells which were completed improperly when first drilled.

5. By using the cosmic-ray intensity at the surface as an arbitrary zero and using absolute deflection in inches per milliampere of ionization current, the log has been calibrated as essentially direct reading. This holds true for any one well, but because of the variation of the combined radiation of the cosmic rays and the gamma-rays of the material on the

surface, it has been found that the apparent cosmic-ray zero varies slightly from well to well.

5. Correct depths to the bottom of each string of casing and exact position of liners have been shown in most cases.

Conclusions.

Since in many cases oil and water are not radioactive to the extent necessary to influence the logging instrument, the gamma-ray unit does not differentiate between oil- and water-sands. In Trinidad, however, it is evident in many cases that the oil-sands show more deflection on the log than do the water-sands. This can be due to at least two causes: first, there may be less porosity of, or more clay in, the oil-sand; second, the oil may be radioactive because of the presence of radon. It is known that radon is absorbed much more readily by oil than by water; hence, if the oil were radioactive and the porosity of the oil and water horizons the same, then the oil-sand would show more deflection than the water-sand. Since a complete knowledge of porosity would be needed to prove or disprove this premise, it is practically impossible at this time to make any positive statement.

In addition to the logging of oil-wells by gamma-ray, another field is the logging of shallow holes for surface geological study. As considerable detail is shown in shales and clays, and as fresh or salt water has no effect on the log, it is believed that more information could be supplied in core-holes with gamma-ray logs than by any other logging technique. This is particularly true, because in many instances radioactive horizons are much more continuous than fossils or porosity values.

There is no doubt that as more areas are studied by the gamma-ray method, additional uses will be found for the device. In addition to gamma-ray logs, a Geiger counter for radioactive analysis of cores will be available and very soon the neutron method of logging will be introduced to Trinidad. This neutron method will provide another radioactive study of the strata and give a second curve from which much more information is expected.

RESERVOIRS UNDER HYDRAULIC AND VOLUMETRIC CONTROLS.*

A. H. Nissan, Ph.D. (Associate Member).

In his extremely detailed book on production of oil, gas, and water, Herold [1] specifies three systems of mechanics for reservoirs of these fluids—namely, hydraulic, volumetric, and capillary controls. The first two controls differ essentially in the nature of $f(t)$ in the formula

$$P = f(t),$$

where P = closed-in pressure of a well after a long time—*i.e.*, reservoir pressure; and t = time. In the hydraulic control, $f(t) = K$ or Kt^0, whilst in volumetric control $f(t) = Kt^2$. In other words, the reservoir pressure in hydraulic control is a constant independent of time—rain-water enters the formation at the outcrop at the same rate as the withdrawal rate of the reservoir fluid and maintains the pressure a constant. In volumetric controls the rate of withdrawal exceeds the rate of entry of water into the formation, and thus the reservoir pressure decreases with time. It is, therefore, admissible to treat the two controls as variants of essentially the same system of mechanics, inasmuch as both operate by virtue of the hydrostatic head on the reservoir fluids and not by any different system, such as the Jamin action. The third control operates, it is postulated, by Jamin principle, and need not be discussed here. Only oil reservoirs under volumetric or hydraulic controls will be studied.

By defining the relationship of pressure and time, and that of a third factor with respect to either pressure or time—such as velocity–pressure relationship—it is possible to construct a whole system of mechanics of reservoir behaviour. Thus if the velocity–pressure relationship is known, together with pressure–time relationship, then it is possible to derive such important functions of reservoir exploitation and evaluation as velocity and time, volume and time, pressure and volume, energy and time, etc.—*i.e.*, all derivatives and integrals of velocity–time, pressure–time, or velocity–pressure functions with respect to any of the three variables.

It is to be noted that, having defined the type of control to be volumetric—hydraulic control being only a special case of volumetric control—and further, having understood its mechanism to be that of flow of a fluid under hydrostatic pressure in a porous medium, it should be possible to derive a velocity–pressure relationship for this type of control from theoretical and experimental considerations. Such a derivation was attempted by Herold himself with the resultant formula :

$$Ve = KP^{\frac{1}{2}}$$

where Ve = velocity of production in units of volume per unit time, and P = the effective working pressure, the closed-in pressure at a depth

* Paper received 24th July, 1941. Written contributions to the discussion of this paper are invited.

opposite the producing sand minus the back pressure against which production is taking place from the sand. The basis of the discussion was Torricelli's theorem.

Other workers, Muskat [2] being a prominent exponent among them, derived a relationship based on Darcy's formulæ and obtained

$$Ve = KP.$$

Thus, the anomaly of one function being derived in two different forms has existed without explanation. This fact was discussed in September 1940, with the suggestion that the anomaly be explained or removed, and a further suggestion for an experimental procedure was outlined by Herold.[3] However, before experiment can be undertaken to verify a theory, it is considered necessary that the theoretical derivation of the functions themselves be examined.

Darcy's work was made directly upon the flow of a fluid in a porous medium like sand, and has therefore been verified experimentally on a great number of samples. Theoretical derivations show that when flow is streamline, or viscous, then the velocity of a fluid in a sand body is related to the pressure by

$$Ve = KP.$$

However, it is pointed out that a relatively small block of a porous material with fluid flowing through it from one extremity to the other is not a reservoir. Thus Darcy's principle is being accepted by the school of thought following Torricelli's theorem, with the reservation that it may not be true for a whole reservoir. This reservation immediately imposes the obligation of studying the meaning of a " reservoir " and its definition in deriving the square-root formula. Herold visualizes a reservoir as a tank containing the liquid under a hydrostatic head with the well, or wells, forming an orifice—a multiple orifice in the case of a multi-well reservoir. In the case of such a tank, the flow is governed by the approximate orifice equation,

$$Ve = C\sqrt{2gH}$$

where H = head of fluid above the orifice, and C and g = coefficient of discharge and gravity constant, respectively. Thus it becomes essential to determine the validity of such a similarity.

A reservoir may be assumed, for simplicity, to be a flat disc of diameter, D, say, 500 ft., containing a liquid under a hydrostatic head, H, of, say, 1000 ft. of the liquid, and being drained by a single well of diameter, d, say, 6 in., centrally situated. In the equivalent reservoir the tank diameter will be $D = 500$ ft., the orifice has a diameter, d, 6 in., and there will be a head of liquid (equal to 1000 ft.) above the orifice. It is assumed that liquid is fed in at such a rate that it is a constant after a time has been allowed for the velocity of the outflow to reach a steady value of Ve. By Bernoulli's theorem, applied to a liquid and taking any two sections in the tank, or the orifice, and working with a unit mass of fluid

$$H_1 + \frac{Ve_1^2}{2g} - W_f = H_2 + \frac{Ve_2^2}{2g}$$

where H_1 and H_2 = potential head (in feet of liquid flowing); $\left(\frac{Ve_1^2}{2g}\right)$ and $\left(\frac{Ve_2^2}{2g}\right)$ = kinetic energy head (in same units); and W_f = frictional head (same units).

$$\therefore \Delta H - W_f = \frac{\Delta Ve^2}{2g}.$$

The overall drop in pressure, from the level of the liquid in the tank to the outlet of the orifice, is H, and is, in fact, made up of a summation of pressure drops over a succession of sections. Three important sections exist. The first is from the top of the tank down a certain length L_1, where the flow, assumed viscous as turbulence in reservoir sands is improbable, is parallel to the sides of the tank. In this section, $\frac{\Delta Ve^2}{2g}$ approaches zero, and therefore only W_f need be evaluated.

From normal viscous flow

$$W_f = \frac{128VeL_1\mu}{\pi D^4 \rho g}$$

$$= kVe\frac{L_1}{D^4}$$

where μ = viscosity of the liquid, ρ = density of fluid, and k = constant, which is seen to be small in magnitude when values are substituted. Thus by the time the liquid has reached a level $(H - L_1)$ its energy content has dropped by an amount $\Delta_1 H$, which is the product of a constant k, the velocity, and the fraction

$$\frac{L_1}{D^4}.$$

This fraction in the example cited has the value of

$$\frac{1000}{(500)^4} = \frac{1}{62{,}500{,}000}.$$

The second section is from the end of this regular streamline flow to the top of the orifice. The flow here is converging towards the orifice, and the pressure drop is not easy to determine. As its exact value is not material in the final argument, let this second pressure drop be $\Delta_2 H$.

The third pressure drop is across the orifice itself, and is equal to $(H - \Delta_1 H - \Delta_2 H)$. Thus in the problem cited, Torricelli's formula would be:

$$Ve = K\sqrt{H - \Delta_1 H - \Delta_2 H}.$$

It is not $Ve = K\sqrt{H}$. However, $\Delta_1 H$ is a very small and, in fact, negligible quantity. Similarly $\Delta_2 H$ is a negligible quantity. Thus, in the case of the tank, it may be written that

$$Ve = K\sqrt{H}$$

without any measurable error. This statement can be easily verified by measuring the differential head across a similar orifice manometrically and comparing it with the total head above. In fact, in many orifice

meters the height of liquid in a tank above the orifice is taken to be the pressure drop across the orifice with good results.

It is conceivable, however, that in certain circumstances $\Delta_1 H$ assumes much more importance relatively to the pressure loss across the orifice $(H - \Delta_1 H - \Delta_2 H)$. Thus if the length L_1 is filled with sand, the total pressure drop across the sand, $\Delta_1 H$, becomes large, and the flow across the entire length of the tank and the orifice will then be according to a compromise function of the first power of pressure for the capillary flow across the sand and the square root of pressure across the orifice. Taking the case to an extreme, the sand may be imagined to be thoroughly cemented and impervious, except for a single capillary tube running through it for the whole length, L_1. In such a case the flow will be governed completely by the linear equation $Ve = KP$, as $\Delta_1 H$ becomes far more important than $H - \Delta_1 H - \Delta_2 H$.

This qualitative analysis may be misleading. The whole flow from a tank 500 ft. in diameter is assumed to flow across a small orifice of only 6 in. in diameter, and thus it may be that however great $\Delta_1 H$ is, $(H - \Delta_1 H - \Delta_2 H)$ may still be predominantly greater. It does, nevertheless, demonstrate the necessity of investigating the adaptability of the model used, tank with an orifice, to represent a reservoir.* A true model would be as follows (see Fig. 1) :

A flat horizontal disc of sand of diameter D ft., and thickness T ft., is covered on both its flat sides by impervious sheaths. Surrounding the outer rim is a ring of the fluid which permeates the disc, this fluid being under a pressure of $\Delta_1 H$ ft. At the centre of the disc is a hole, through which the fluid flows down, through a tube, to an orifice, diameter d ft., placed at a distance of H ft. below the top of the tank; $\Delta_2 H$ represents the pressure loss through this tube. Thus the total head across the sand, the connecting tube, and the orifice is H as before.

To derive the equation of the flow of such a reservoir it is possible to calculate Ve across the sand from $\Delta_1 H$ and the characteristics of the sands, and then determine the pressure drop across the orifice for the value of Ve so found. Thus the relative importance of $\Delta_1 H$ to the pressure drop across the orifice may be ascertained. To follow this procedure would, however, involve using Darcy's law for the radial flow of the fluid across the sand, and as the applicability of this law to flow in reservoirs is the point at issue, the step might not be justified, at least not at this point. Thus a yet simpler and more " ideal " model may be constructed.

The new model (Fig. 2) is the same in shape and dimensions as the previous reservoir, except for replacing the sand body by straight uniform capillary tubes of diameter δ ft. each, extending radially from the centre to the periphery of the disc. In order that these capillaries may represent the sand body of porosity M, the length of these tubes will be $\frac{D}{2}$ ft., and the total number is such that :

$$n \cdot \frac{\pi}{4}\delta^2 \frac{D}{2} = \frac{\pi D^2 T M}{4}$$

* This is particularly the case as it has been stated : " A solution tank, filled with sand or other porous, insoluble material . . . performs in accordance with the same laws as one without the porous material."—Herold,[1] p. 331.

where n = number of capillaries, δ = diameter of capillaries, ft., D = diameter of disc., ft., T = thickness of disc, ft., and M = porosity of sand, fraction. (The central hole in the disc is ignored. The capillary model

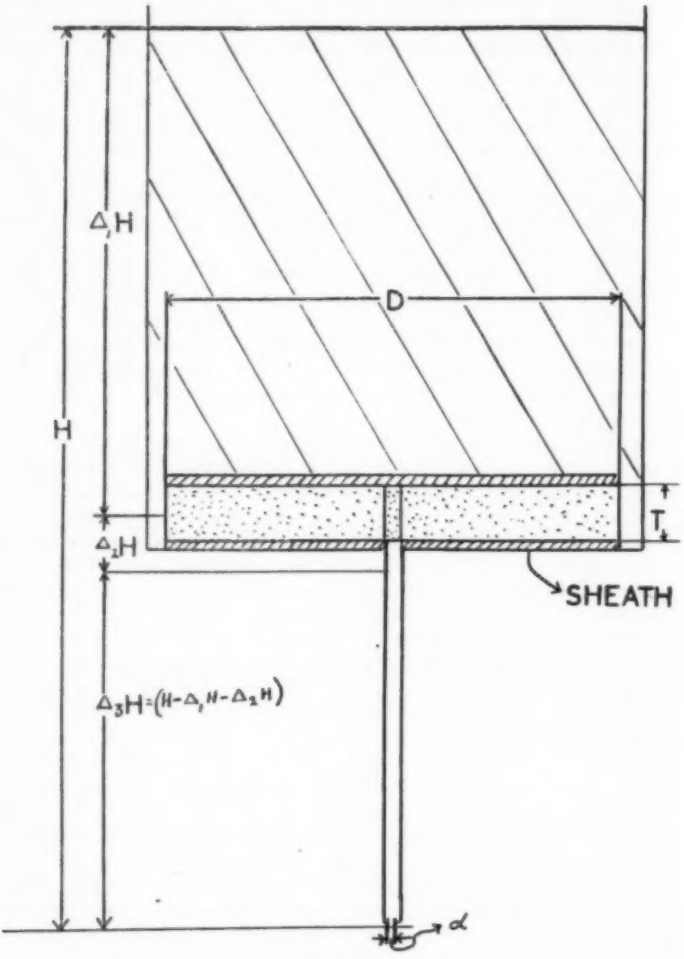

FIG. 1.

does not represent the sand from a permeability viewpoint, but this is immaterial to the argument.)

Before solving the problem it may be helpful to give typical figures for the various constants in order to appreciate their ratios and relative importance. The diameter D of the tank may be taken to be 1000 ft., as this figure is used in calculating the effective drainage of wells. The

diameter of the orifice, d, may be taken as $\frac{1}{2}$ ft., and that of the capillary, δ, may be 0·001 ft. Thus :

$$\frac{D}{2} : d : \delta = 500{,}000 : 500 : 1$$

T, the thickness of the sand, may be taken as 50 ft., M, the porosity, as 20 per cent., whilst $\Delta_1 H$ may be considered to be, for simplicity, 1000 ft. of the fluid.

The flow will be assumed to be viscous in each capillary and will be calculated for a drop of $\Delta_1 H$ ft. in pressure. Then,

$$V_c = \frac{2\pi\delta^4 \Delta_1 H \rho g}{128\mu \,.\, D}$$

where V_c = volumetric rate of flow, cu. ft./sec., ρ = density of fluid, lb./cu. ft., μ = viscosity of fluid, poundle sec./ft.^{2}, and g = gravitational constant (32·2). The total flow through all the capillaries is then nV_c, where

$$n = \frac{2DTM}{\delta^2}.$$

Thus the total flow is given by

$$Vc = nV_c = \frac{4\pi\delta^2 TM\Delta_1 H\rho g}{128\mu}.$$

This volume is flowing through an orifice of d ft. in diameter. Hence the mean linear velocity through the orifice,

$$v_0 = \frac{16\pi\delta^2 TM\Delta_1 H\rho g}{128\mu\pi d^2} = \frac{16\delta^2 TM\Delta_1 H\rho g}{128\mu d^2}.$$

The pressure loss across the orifice, $(H - \Delta_1 H - \Delta_2 H)$ is given by

$$v_0 = C\sqrt{2g(H - \Delta_1 H - \Delta_2 H)}$$
$$= \frac{16\delta^2 TM\Delta_1 H\rho g}{128\mu d^2}.$$

Thus calling $(H - \Delta_1 H - \Delta_2 H)$, $\Delta_3 H$, then,

$$\sqrt{\Delta_3 H} = \frac{16\delta^2 TM\rho g}{128C\mu d^2\sqrt{2g}}(\Delta_1 H).$$

Again, separating the properties of the fluid from those of the reservoir,

$$\Delta_3 H = \left[\left(\frac{\delta^2 TMg}{8Cd^2\sqrt{2g}}\right)\left(\frac{\rho}{\mu}\right)(\Delta_1 H)\right]^2.$$

It is instructive to solve the problem taking the dimensions given for the typical reservoir and using three types of liquids. The first will be an oil of 58 lb./cu. ft. and four poises/viscosity, the second an oil of the same density and one-fifth the viscosity—*i.e.*, 80 centipoise—and the third water. The porosity is assumed to be 0·20.

Case I. $$\Delta_3 H = \left[\left(\frac{(0{\cdot}001)^2 \times 50 \times 0{\cdot}2 \times 32}{8 \times 0{\cdot}6 \times (0{\cdot}5)^2\sqrt{64}}\right)\left(\frac{58}{4 \times 0{\cdot}067}\right)(1000)\right]^2.$$
$$= 51{\cdot}8 \text{ ft. of fluid flowing.}$$

Case II. $\Delta_3 H = \left[\left(\frac{(0{\cdot}001)^2 \times 50 \times 0{\cdot}2 \times 32}{8 \times 0{\cdot}6 \times (0{\cdot}5)^2 \times \sqrt{64}}\right)\left(\frac{58}{0{\cdot}8 \times 0{\cdot}067}\right)(1000)\right]^2$.

$= 1296$ ft. of fluid flowing.

Case III. $\Delta_3 H = \left[\left(\frac{(0{\cdot}001)^2 \times 50 \times 0{\cdot}2 \times 32}{8 \times 0{\cdot}6 \times (0{\cdot}5)^2 \sqrt{64}}\right)\left(\frac{62{\cdot}4}{0{\cdot}00067}\right)(1000)\right]^2$.

$= 9{\cdot}63 \times 10^6$ ft. of fluid flowing.

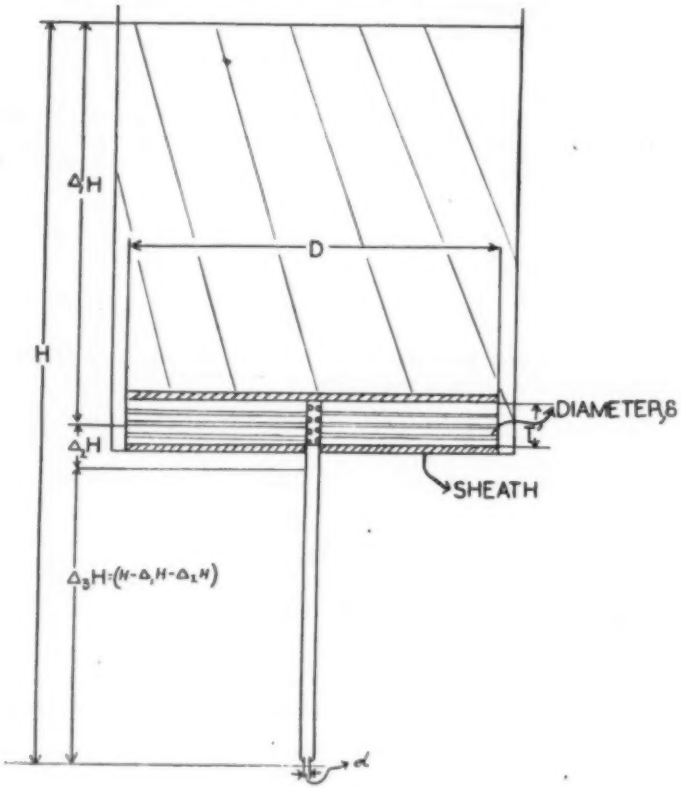

FIG. 6.

Thus in the first case the flow will be almost entirely governed by the formula

$$Ve = KP$$

as only 51·8 ft. of head are lost across the orifice, compared with 1000 ft. lost across the "sand." In Case II the flow will be governed by a compromise between the two formulæ under discussion, since the head of

fluid lost across the "sand" is approximately equal to the head lost across the orifice. Thus,

$$Ve = K_1P_1 + K_2P_2^{\frac{1}{2}}$$

where $P_1 + P_2 = P$, the total pressure. In the third case the head lost across the "sand" is almost negligible compared to the head lost across the orifice. Thus it would appear that the flow would conform to the law,

$$Ve = KP^{\frac{1}{2}}.$$

From these three cases it becomes evident that a general form of the flow formula is given by

$$Ve = K_1P_1 + K_2P_2^{\frac{1}{2}}$$
$$P_1 + P_2 = P$$

with either P_1 or P_2 vanishing in extreme cases.

Here it should be stated that the capillary tube model does not represent a true sand, as it differs in two major respects from reservoir formations. The model serves a purpose, however, and this will be elucidated before the differences between the model and a sand are discussed. It is seen that when a reservoir model is constructed in the shape of a tank and an orifice and further brought into approximate resemblance with a true reservoir, Torricelli's formula does not apply except in certain peculiar cases. These cases are peculiar in that the resistance offered to the flow by virtue of frictional forces is small. This may be either because the viscosity of the fluid is very low (cf. calculations above) or because the permeability of the formation is very high. Thus it is possible that a tank loosely filled with sand and fitted with an orifice will behave as if the sand were absent in so far as the flow formula may still be $Ve = KP^{\frac{1}{2}}$. This, in fact, explains the footnote on p. 149. It can only be supposed that that statement was based upon experiments conducted with a relatively wide and shallow tank filled with loosely compacted sand and using water for the fluid—*i.e.*, with a high permeability and low viscosity conditions. Deep sands are usually compact bodies, and oils are usually viscous, and thus it must be concluded that flow in sands cannot be represented by Case III in the problem, and that it must occur according to either Case I or II. Stated in different terms, it is highly improbable that the general formula

$$Ve = K_1P_1 + K_2P_2^{\frac{1}{2}}$$

would reduce to the form $Ve = KP^{\frac{1}{2}}$ in dealing with oil reservoirs. It is to be noted that this statement is based on the method of analysis proposed in formulating the square-root formula. Whether the general formula may not be reduced to a simpler form, as it is difficult to separate P into P_1 and P_2, is yet to be found.

The capillary model differs from a sand body, in the first instance, in that, while it represents its porosity, it does not necessarily represent the more important function of permeability. However, the disc of capillary tubes may be made to represent both these characteristics of the sand as

follows : assuming the two discs to be both of the same diameter D, then the porosity is accounted for by making

$$n \cdot \frac{\pi}{4} \delta^2 \frac{D}{2} = \frac{\pi D^2 T M}{4}$$

as before. The model can then be made to represent the sand from a permeability viewpoint, *taking the sand as a whole* by making δ of such dimensions, that the resistance offered to flow by both discs *over the entire path* $\frac{D}{2}$, is the same—*i.e.*, making $\Delta_1 H/Ve$ the same in both. It was seen that for the capillary model

$$\frac{\Delta_1 H}{Ve} = \alpha \frac{\mu}{\delta^2 T M}$$

where α = constant which can be determined by substitution. The value of $\Delta_1 H/Ve$ for radial flow in a sand body of permeability K is given by

$$\frac{\Delta_1 H}{Ve} = \beta \frac{\log\left(\frac{D}{d}\right)\mu}{kT}$$

where β = a constant. Thus by making

$$\alpha \frac{\mu}{\delta^2 T M} = \beta \frac{\log\left(\frac{D}{d}\right)\mu}{kT}$$

or

$$\delta = \left[\frac{\alpha}{\beta} \cdot \frac{k}{\log\left(\frac{D}{d}\right) M}\right]^{\frac{1}{2}}$$

The capillary model will represent the sand body as a whole statically (porosity) and approximately dynamically (permeability). In model experiments, at least, these relations should be satisfied. It is still important to realize that no section or part of the model represents a corresponding section or part of the sand. This fact constitutes the second major difference.

In the capillary model flow is in one dimension and at a uniform linear speed throughout the length $D/2$. In a sand body the flow is two-dimensional, converging towards the centre with the linear speed of flow increasing with approach to the centre. Thus at any radius, r, from the centre the linear velocity v_r is given by

$$v_r = \frac{Ve}{2\pi r T}$$

varying from nearly zero at the periphery of the reservoir to the maximum value at the well. This is the average linear speed per square foot of sand face at radius r from the well. The actual average linear speed of flow of the fluid can only be estimated by supposing that the sand is ideally uniform in porosity—*i.e.*, over each square foot of sand-face the voids

occupy an area of M, the fractional porosity. Thus the actual average linear flow of the fluid at radius r is :

$$v'_r = \frac{Ve}{2\pi rTM}.$$

At the sand-face the average linear speed is, then, $\frac{Ve}{\pi dTM}$.

It becomes evident after this discussion that it is impossible to construct a model for a reservoir by means of capillary tubes. Thus, after serving its specific purpose of illustrating the remoteness of the probability that the square-root formula is the acting law for reservoir behaviour, this model has to be discarded, and work must be confined solely to studies of a reservoir composed of porous material. The only formula which can be used to calculate the loss of head due to frictional, or viscous, resistance in such a reservoir is the well-known radial flow equation based upon Darcy's law. By taking

$$v_r = \frac{-Ve}{2\pi rT}$$

$$\text{and } v_r = \frac{-k}{\mu} \cdot \frac{dp}{dr}$$

i.e.,

$$\frac{Ve\mu}{2\pi Tk} \cdot \int_{d/2}^{D/2} \frac{dr}{r} = \int_{P'_1}^{P'_2} dp.$$

Then

$$\Delta_1 H \propto \Delta P \propto \frac{Ve\mu}{2\pi Tk} \log\left(\frac{D}{d}\right).$$

Thus $\Delta_1 H$ may be calculated for a sand. This gives the frictional resistance or P_1 in the general formula

$$Ve = K_1 P_1 + K_2 P_2^{\frac{1}{2}}.$$

It is to be noted that while the fluid is practically at rest at the rim of the reservoir, it is accelerated to a definite velocity at the sand-face, or, to simplify the problem, at the horizontal cross-section of the well at the level of the top of the sand. The speed here is :

$$v_0 = \frac{4Ve}{\pi d^2}.$$

By applying Bernoulli's equation to the outer rim of the reservoir and this section of the well, it is found that :

$$P_D = P_d + \left(\frac{4Ve}{\pi d^2}\right)^2 \Big/ 2_g + W_f.$$

where P_D = pressure at rim of reservoir, and P_d = pressure at well opposite sand,

or

$$\Delta P = \left(\frac{4Ve}{\pi d^2}\right)^2 \Big/ 2_g + W_f.$$

In terms of head of fluid,

$$H = K'Ve + K''Ve^2$$

Thus, in this reservoir, as in the model, the pressure drop consists of two items : one, representing the loss in head due to the increase in the kinetic

energy of the fluid from zero to that existing at the bottom of the well, is proportional to the square of the velocity; and the second, representing the frictional head, is proportional to the first power of the velocity. For a sand reservoir the velocity–pressure relationship may be written, as in the case of the inaccurate model,

$$Ve = K_1P_1 + K_2P_2^{\frac{1}{2}}$$

where $P_1 + P_2 = P$. Finally it remains to be ascertained whether P_1 or P_2 are of equal or of different relative importance.

Working again in heads of fluid, the kinetic energy head is given by:

$$v_0 = C\sqrt{2g\Delta_3H}$$

or

$$\Delta_3H = \frac{v_0^2}{2C^2g} = \frac{Ve^2}{4\pi^2d^4C^2} = \frac{Ve^2}{14{\cdot}2d^4}$$

where Δ_3H = kinetic energy head, ft., Ve = volumetric velocity, cu. ft./sec., d = diameter of well, ft., and g and c are constants, 32 and 0·6 respectively. The frictional head may be calculated from the normal radial flow formula for liquids flowing in homogeneous porous media, as it is the only formula which is left and which represents the facts completely. Applying F.P.S. units to the formula,

$$\frac{\Delta_1H \times \rho}{33 \times 62{\cdot}4} = \frac{\mu .\ Ve\,(28{,}320)\,.\,2{\cdot}3\log\left(\frac{D}{d}\right)}{2\pi kT(30{\cdot}48)}$$

where Δ_1H = frictional head, ft., ρ = density of fluid, lb./cu. ft., μ = viscosity of fluid, centipoises, D = diameter of reservoir, ft., k = permeability of reservoir, darcys, and T = thickness of reservoir, ft.

Thus

$$\Delta_1H = \frac{28{,}320 \times 2{\cdot}3 \times 33 \times 62{\cdot}4}{2 \times 30{\cdot}48\pi}\,\frac{\mu Ve\log\left(\frac{D}{d}\right)}{\rho kT}$$

$$= 7 \times 10^5\,\frac{\mu Ve\log\left(\frac{D}{d}\right)}{\rho kT}.$$

Hence

$$\frac{\Delta_1H}{\Delta_3H} = 14{\cdot}2 \times 7 \times 10^5\,\frac{\mu\left[\log\left(\frac{D}{d}\right)\right]d^4}{\rho kTVe} = \frac{9{\cdot}94 \times 10^6\,\mu\left[\log\left(\frac{D}{d}\right)\right]d^4}{\rho kTVe}.$$

To see whether Δ_3H, the kinetic energy head, is important at all, an extreme case will be taken where the numerator terms will be given small values and the denominator variables large values obtained in reservoirs. Thus assuming,

D = 100 ft.,
d = 3 in. = 0·25 ft.,
T = 500 ft.,
k = 2000 millidarcys,
ρ = 58 lb./cu. ft.,
μ = 50 centipoises.

Thus :

$$\frac{\Delta_1 H}{\Delta_3 H} = \frac{10^7 \times 50 \times 2{\cdot}6 \times 0{\cdot}0039}{58 \times 2 \times 500}\left(\frac{1}{Ve}\right)$$
$$= \frac{87{\cdot}5}{Ve}.$$

With a production from this well of 1100 tons per day—*i.e.*, $Ve = 0{\cdot}5$ cu. ft./sec.—$\Delta_3 H$ is only $\frac{\Delta_1 H}{175}$.

It is therefore seen that, except in very special circumstances where both the permeability of the reservoir and the rate of production are extremely high, the kinetic energy head is a negligible quantity compared to the frictional head. Thus it must be concluded that in practically all oil reservoirs under volumetric control the flow of oil is accurately * represented by Darcy's law, *i.e.*,

$$Ve = KP.$$

Conclusions.

1. An anomaly appeared to exist in deriving the velocity–pressure relationship, for reservoirs under volumetric or hydraulic controls, by two methods. The two equations were $Ve = KP^{\frac{1}{2}}$ and $Ve = KP$.

2. A study of the two methods reveals the fact that the assumption made in applying only orifice equations to the problem are not justifiable, and that if a truly representative model be constructed the anomaly disappears and a single equation is the result :

$$Ve = K_1 P_1 + K_2 P_2^{\frac{1}{2}}.$$

3. It is further shown that P_2 is negligible in oil reservoirs under volumetric or hydraulic controls and therefore the equation becomes $Ve = KP$.

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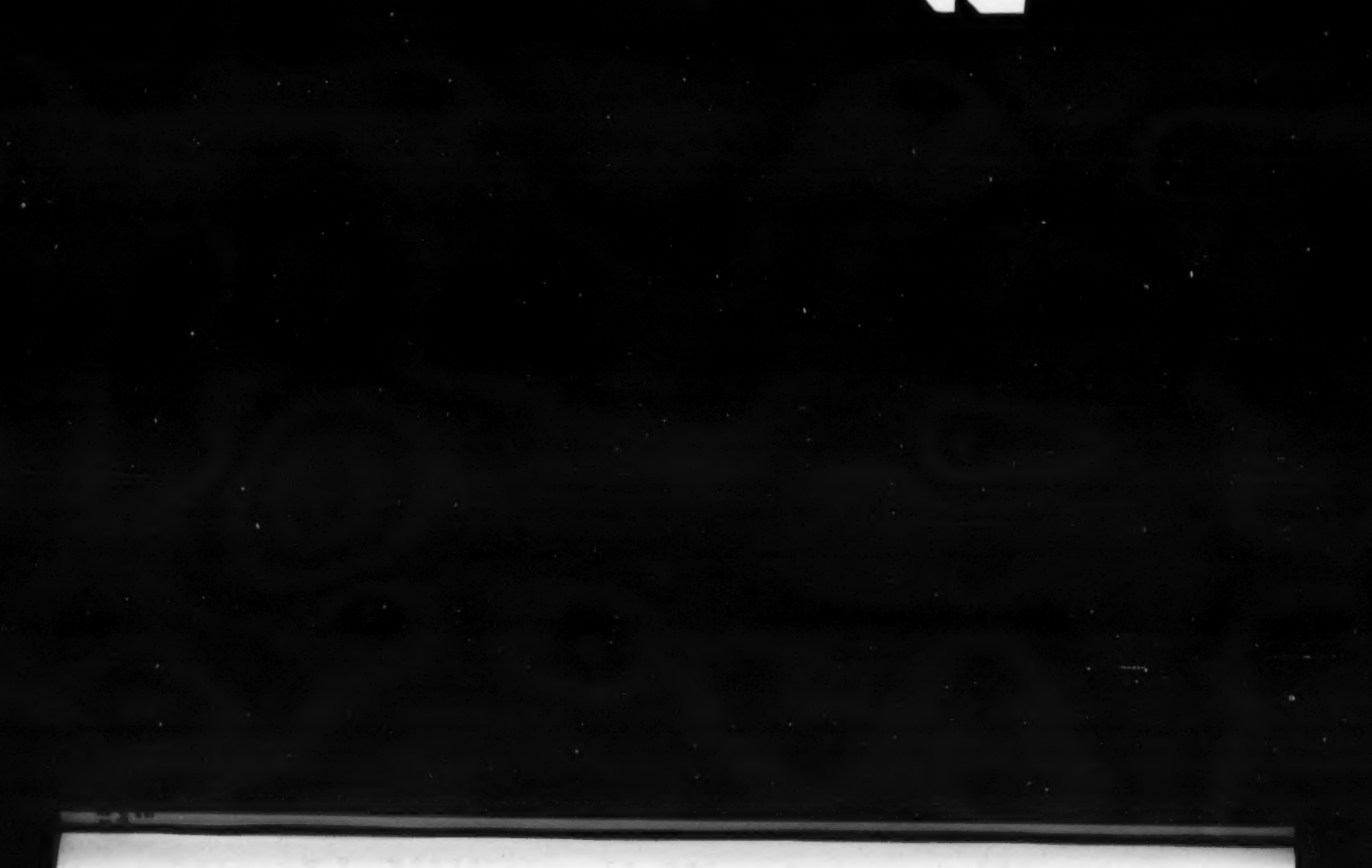
* This is meant in a relative sense only. Experiments in this Department have shown that at extremely low rates of flow Darcy's law does not apply to the flow of air through rocks.[4]